TITLE: Design Aspects of the Elastic Trailing Edge for an Adaptive Wing

Design Aspects of the Elastic Trailing Edge for an Adaptive Wing

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ABSTRACT

According to predictions of market researchers a large growth in numbers of passengers as well as of airfreight volume can be expected for the civil transport aircraft industry. This will lead to an increased competition between the aircraft manufacturers. To stay competitive it will be essential to improve the efficiency of the new aircraft generation. Especially the transonic wings of civil aircraft with their fixed geometry offer a large potential for improvement. Such fixed geometry wings are optimized for only one design point characterized by the parameters altitude, mach number and aircraft weight. Since these vary permanently during the mission of the aircraft the wing geometry is only seldom optimal. As aerodynamic investigations have shown one possibility to compensate for this major disadvantage lies in the chordwise and spanwise differential variation of the wing camber for mission duration. This paper describes the design of a flexible flap system for an adaptive wing to be used in civil transport aircraft that allows both a chordwise as well as a spanwise differential camber variation during flight. Since both lower and upper skins are flexed by active ribs, the camber variation is achieved with a smooth contour and without any additional gaps. This approach for varying the wing's camber is designed to be used for replacement and enhancement of a given flap system. In addition the kinematics of the rib structure allows for adaptation of the profile contour to different types of aerodynamic and geometric requirements.

1. INTRODUCTION

Already Otto Lilienthal who is also called the "Father of Modern Aviation", recognized through extensive observations of bird's flight that camber is essential for generating lift. With this knowledge he managed to perform the first successful glide of a human being in 1891. Many others followed. The wings of these first aircraft where of fixed geometry where the flight control was realized by weight transfer and a nearly artistic body control of the pilot. It was soon discovered that a variation of the camber enabled improved maneuverability. In 1903 this was the case with the first motorized flight of the Wright brothers, where lateral control was realized by twisting the wings in opposite direction to each other. But a twisting of the wings for lateral control did not remain practicable very long because structural stiffness of the airplanes increased with the need for more performance. Thus, in 1910 Henry Farman introduced the first ailerons. Due to continuously increasing weight and size of the airplanes high lift flaps soon became necessary in order to increase the camber and therefore the lift during the start and landing phase. Since 1919 these are in use [1].

Basically, this principle application of flaps has not changed to date, also not in modern transonic civil transport aircraft. With the exception of the starting and landing phase, no considerable use of flaps and therefore change of camber is being performed. During most of the flight the wing is of fixed geometry and therefore of constant camber. The major disadvantage of fixed geometry wings is that they can only be optimized for one design point characterized by the parameters altitude, mach number and aircraft weight. Since these vary continuously during the mission of the aircraft the wing geometry is only seldom optimal. The development of wings with fixed geometry is therefore always the best compromise between design and off-design point where a better performance at the design point leads to a worse off design performance. E.g., for a civil aircraft it may be necessary to fly fast and at low altitude with light weight over a short stretch one day. The next day it may be beneficial to fly at high altitude with maximum load, and at an economical velocity for a much longer range. In the first case the lift coefficient could be only 0.08 whereas in the second case it might be as large as 0.4. Thus, values of the maximum cruise lift coefficient can be as much as five times the minimum for most airliners [2]. In addition, the airplane weight drops up to 30% during a long range mission due to fuel consumption [3]. Such significant changes in flight conditions can be compensated sufficiently by varying the wing camber for mission duration to obtain near optimum geometry for the flight conditions to be encountered. This approach has the potential to lead to a considerable improvement of the aerodynamic and structural efficiency of an aircraft.

The introduction of new technologies such as camber variation to improve aircraft efficiency is essential for the future success of the airplane manufacturers. Especially since market research predicts a very positive development for the aircraft industry an increasing competition is to be expected: The civil aircraft industry, has shown strong economic growth during the past decades with an average increase of 6% per year. For the next 20 years the large airplane manufacturers Airbus Industry and Boing expect growth rates of around 4.5% per year [4]. This means that over the next 15 years the number of passengers is expected to double, the amount of airfreight probably will increase even more. The expectation of a steady growth in aircraft industry over the next 20 - 25 years is justified when taking into consideration that only a very small part of the world population is responsible for a great deal of the world wide air traffic today: e.g., US-citizens make up only 4.6% of the world population but hold 41% of the worldwide km flown per passenger. In contrast, China and India together represent 37% of the world population but hold only 3.4% of the worldwide km flown per passenger. If in the future the worldwide population flies as much as US-citizens today, and taking into consideration the predicted world population growth from 5.6 billion to 8.3 billion by the year 2025, then the km flown per passenger would rise by a factor of 13. At a growth rate of 4.5% per year this factor would first be reached in 60 years. Assuming a healthy worldwide economic development there is no danger of market saturation in the near future [5, 6].

2. VARIABLE CAMBER PRINCIPLE

It is of special interest to achieve a chordwise and spanwise differential camber variation with one structural system providing a smooth contour having no additional gaps. The camber variation concentrates on the trailing edge since under aerodynamic as well as structural aspects this region has the highest efficiency [7]. On civil transport aircraft the

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Fowler flaps and ailerons are positioned in this region (see Fig. 1).

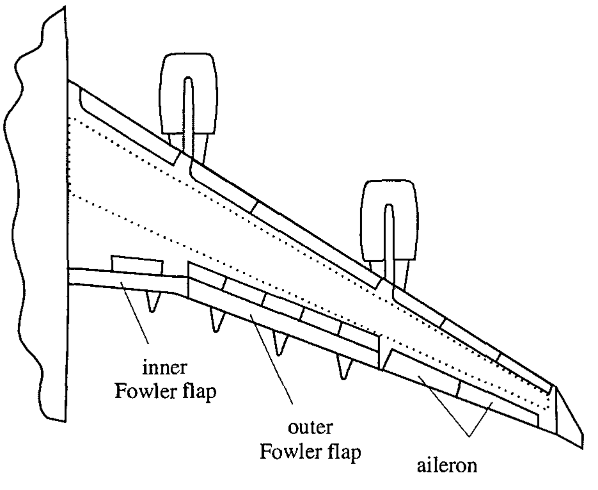

Fig. 1: Flaps of a civil transport aircraft

Therefore it is important to develop a cambering system that on the one hand can be used to enhance the Fowler flaps by an additional cambering function and on the other hand enables a complete substitution of an aileron. Fig. 2 shows this principle for a Fowler flap with enhanced cambering.

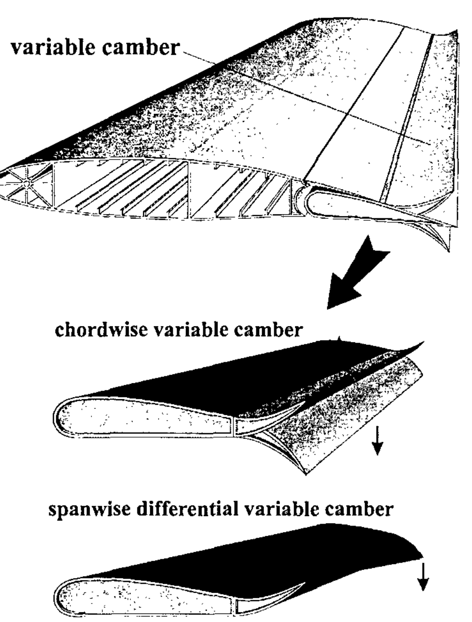

Fig. 2: Chordwise and spanwise differential camber variation of Fowler flaps with an enhanced cambering function

The cambering system should also be constructed such that during its actuation the structural stiffness does not change. This ensures that sudden changes in loading caused by gust for example, lead to failure. When the Fowler flaps are enhanced by an additional cambering function they should still retain their primary function as a high-lift device. If the ailerons are replaced with such a cambering system the actuators have to be positioned inside the structure. In addition it is important to be able to adapt the profile contour to different types of aerodynamic and geometric requirements for the median line. Considering the remarks made above, the following basic requirements can be defined:

- the structural system has to be suitable for replacement and enhancement of a given flap system
- a chordwise and spanwise differential camber variation has to be achieved with one structural system
- a smooth contour having no additional gaps has to be provided
- the actuators have to be integrated into the flap structure
- the profile contour has to be able to be adapted to different types of aerodynamic and geometric requirements
- the structural stiffness is not allowed to change during actuation

Both chordwise and spanwise differential camber variation are expected to have various effects on aerodynamic and structural efficiency. The following improvements over fixed geometry wings are expected:

- higher aerodynamic efficiency due to optimized lift/drag (L/D) ratio leads to an extended cruise range and reduction in fuel consumption
- improved operational flexibility by shifting the maximum L/D ratio to higher values
- extended buffet boundary enlarges the operative range and reduces structural weight
- reduction of wing root bending moment leads to a reduction of structural weight
- increased stretch potential leads to a significant reduction of development costs

A general description of the effects of these two types of camber adjustments for a typical civil transport aircraft of the early 90's is given in the next two sections.

2.1 Chordwise camber variation

The chordwise camber variation is mainly responsible for the improvement of the aerodynamic efficiency by optimizing the L/D ratio for present flight situation. This directly leads to a reduction in fuel consumption. The L/D ratio results from the wing data, altitude, mach number, and aircraft weight. Special emphasis is given to the weight loss due to fuel consumption (>30% during a long distance flight) which has considerable negative influence on the L/D ratio of the aircraft that can be compensated by a camber variation. Thus, at the beginning of the flight the camber has to be large, to decrease later with the reduction in weight. As shown in Fig. 3, the chordwise camber variation leads to an optimization of the L/D ratio according to the present flight situation between 3% to 10%. The dashed curve indicating the variable camber presents the envelope of a number of optimal camber positions. This results in an extended cruise-range in comparison to a fixed wing (solid line) by shifting the maximum L/D to up to 12% higher C_L-values. Another advantage of a wing with variable camber consists in the improved buffet boundaries. This is equivalent to an enlarged speed range meaning that, for instance, during the landing phase a larger time range is available so that unnecessary holding patterns can be avoided [7, 8].

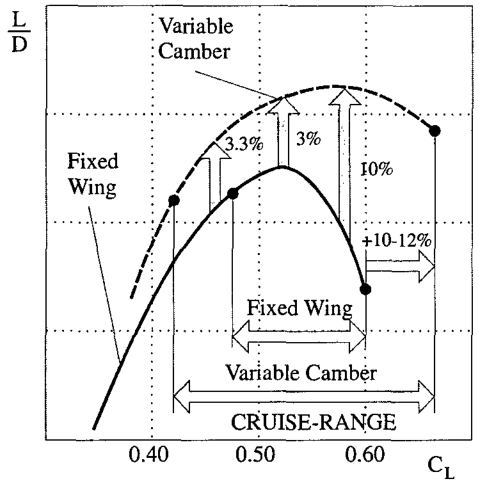

Fig. 3: Variable camber effect on L/D [7, 8]

2.2 Spanwise differential camber variation

Besides L/D optimization, this system can be used to gain control over dimensioning load cases such as the maneuver situation where the pilot has to execute a 2.5g maneuver load. In Fig. 4 the potential of spanwise camber control is demonstrated. Compared with the typical lift distribution for optimal performance (solid line) the differential deflection leads to a significant reduction of the root bending moments (RBM) through redistribution of the spanwise lift distribution (dashed line). This is achieved by cambering the inboard and de-cambering the outboard wing. In all a 12 - 15% reduction of the RBM is achieved leading to an increase of the payload/structural weight ratio. When combined with a chordwise camber variation a wing with a high adaptability towards different types of requirements can be provided [3, 9].

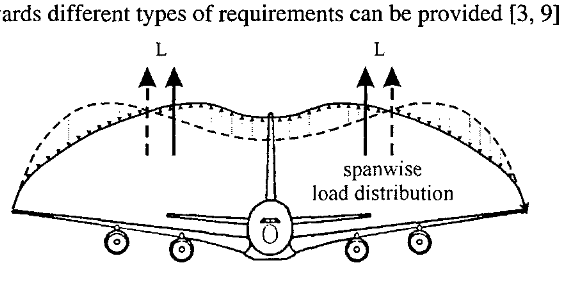

Fig. 4: Load control by means of variable camber [3]

3. STRUCTURAL CONCEPT

As mentioned the cambering system has to be suitable for replacement of an aileron as well as enhancement of a Fowler flap. Under structural mechanical aspects it is more demanding to enhance a given flap structure with a cambering system since there is less space available and also the stiffness of the flap is much more critical. This means that when a solution can be found that can enhance a single flap it is all the more usable to substitute a total flap. Therefore the approach demonstrated in this paper is presented for a Fowler flap with an enhanced cambering system. As shown in Fig. 5, the basic concept for the design of the flexible Fowler flaps consists of replacing the stiff inflexible rib elements reaching into the flexible section (dark gray) by active deformable elements with high stiffness. This means the skin fields must then be able to glide on the flexible ribs. The basic design of the front fixed part (light gray) is changed as little as possible to avoid a totally new design concept for the fixed flap section [10, 11, 12].

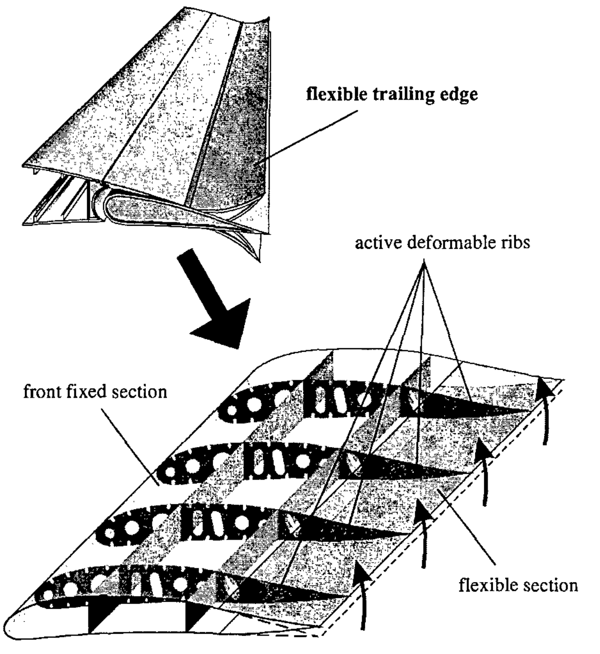

Fig. 5: Position and distribution of active deformable ribs in the Fowler flaps

The flexible ribs were realized by combining separate plate like elements with revolute joints having the kinematics described in Fig. 6a. Fig. 6b represents one rib of the flexible section. Each rib only has to be actuated at one single point. The rotation of the driven element is transferred gradually from element to element by the kinematics and this way provides the wanted rib contour.

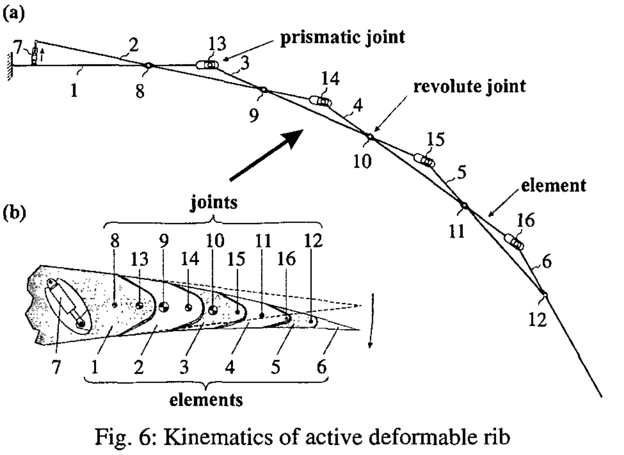

Fig. 6: Kinematics of active deformable rib

The kinematics will be described by referring to the first three elements (1 to 3): An actuator (7) is supported by the fixed first element (1) which represents the continuation of the rib in the front fixed section (Fig. 5). The actuator (7) drives a second element (2) which is attached to the first element (1) by a revolute joint (8). The second element (2), too, is connected to the third element (3) by a revolute joint (9). In addition the third element (3) is connected to the first one (1) by a prismatic joint (13). By putting the actuator (7) into motion the second element (2) rotates about revolute joint (8). Due to revolute joint (9) the third element (3) rotates about revolute joint (8), too, and is supported by the first element (1) in prismatic joint (13). This way the third element (3) is bent towards the second one (2) about revolute joint (9). These kinematics can be applied to an unlimited number of elements. To provide functionality at least three elements must be used. A variation of the individual length between the joints (e.g. the

region between the joints (8) and (9), (8) and (13) as well as (9) and (13)) allows a precise adjustment of the rib contour.

Fig. 7. shows a modification of the active deformable rib in Fig. 6 with an additional lever (17) in order to reduce structural loads and the driving force. The kinematics of the active deformable rib remains the same with the exception that the actuator (7) is attached to lever (17) and not to element (2). The lever is connected to the first element (1) by revolute joint (8) and with element (4) by a prismatic joint (18). To provide functionality at least four elements must be used.

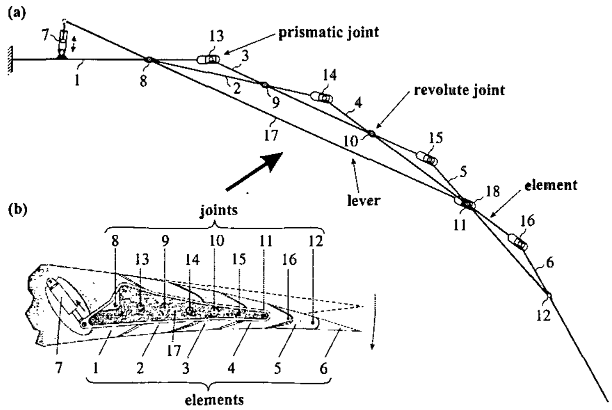

Fig. 7: Kinematics of flexible rib with additional lever

Fig. 8 shows how the elements are configured using the third element (3) as an example. For the purpose of good load transmission a symmetrical design was developed. In the horizontal projection the elements have the shape of a tuning fork. The element itself consists of one inner and two outer parts which are attached to each other with an adhesive. Every element is provided with two bore holes for the prismatic and revolute joints.

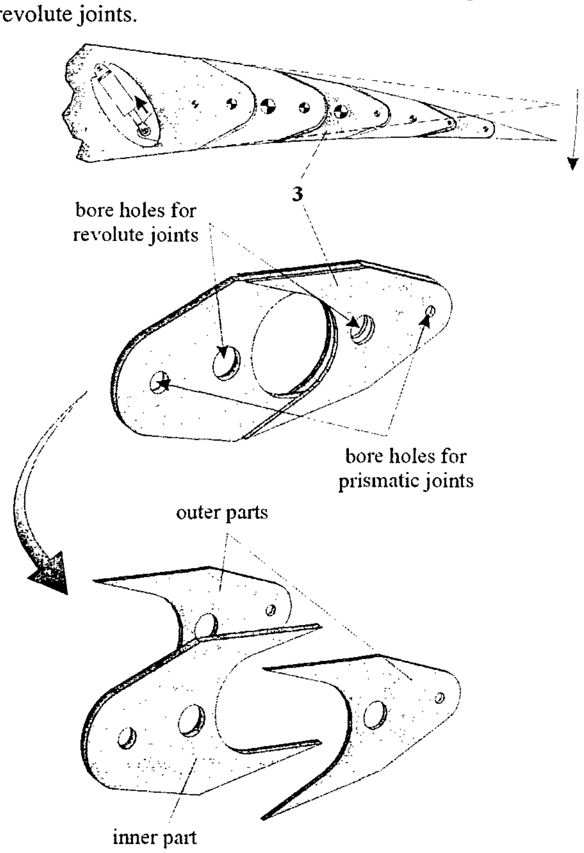

Fig. 8: Geometry of an element

An aluminum model of the flexible rib is demonstrated in Fig. 9. It shows the rib in its neutral position as well as at maximum upper and lower deflection. A carbon fiber composite rib has also been constructed. It has stiffness similar to the aluminum version with about 40% reduction in weight. For this rib a spindle drive is used as actuator.

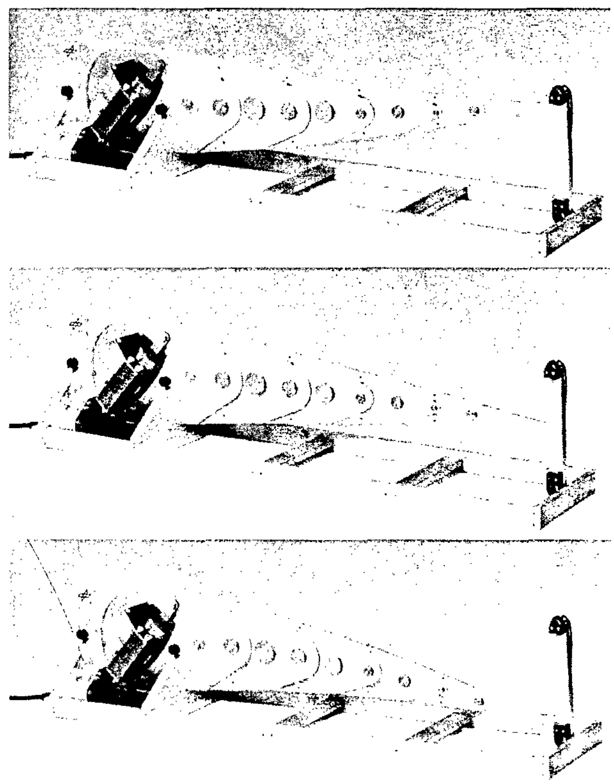

Fig. 9: Active adjustable rib in neutral position and total upper and lower deflection

The design of the upper and lower skin is presented in Fig. 10. As shown in section A-A the stringers are interrupted by a linear slide bearing. At the upper and lower part of the rib elements counterparts are attached which make up the inside part of the linear slide bearing. These bearings allow a chordwise displacement between the rib and the upper and lower skin. Simultaneously a lift-off of the upper and lower skin due to aerodynamic loads is prevented. At the trailing edge the upper and lower skins are combined by a linear slide bearing allowing a chordwise translation here, too. In addition the trailing edge can easily be replaced if damaged.

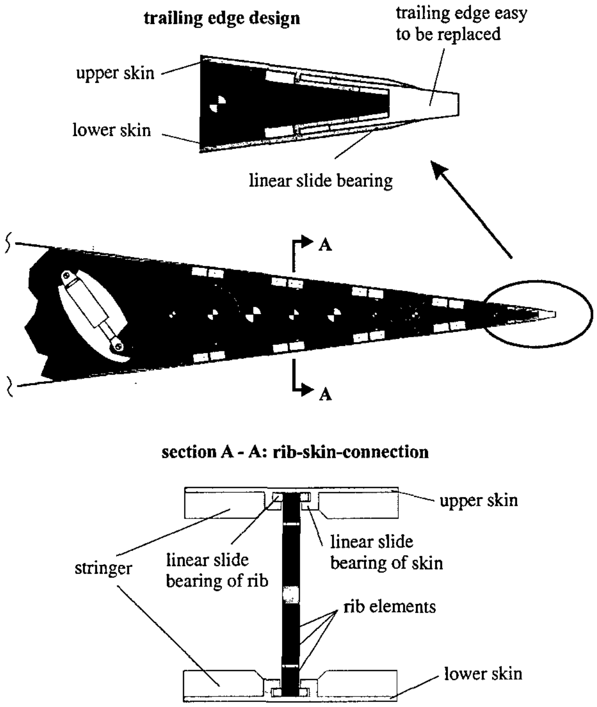

Fig. 10: Design of upper and lower skin

As described every rib element is connected to the upper and lower skin by linear slide bearings. These are individually dimensioned and positioned on the skin according to the loading that appears. Fig. 11 shows that in the front region where the second elements are located the linear slide bearings are shorter than towards the end. This is due to the larger displacement between rib and skin at the trailing edge.

In order to achieve a high stiffness of the linear slide bearings on the skin it is important to position the stringer in their middle. Depending on the available space the stringer have to be varied in their height according to the maximum needed and maximum possible values [13].

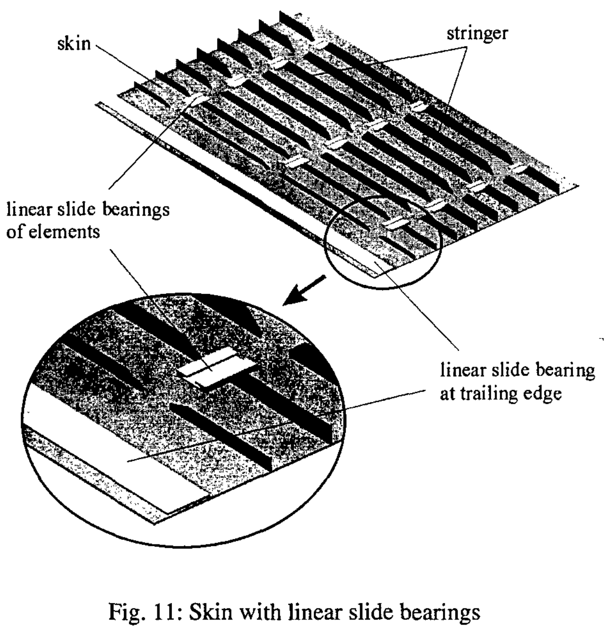

Fig. 11: Skin with linear slide bearings

For reasons of a better description of the kinematics the ribs in Fig. 6 and Fig. 7 are driven by a linear actuator. Since with this type of activation every rib has to be driven by an individual actuator, the number of them is quite high. Moreover the total loading is introduced directly into the actuator requiring a powerful drive. By using a transmission beam together with a wedge system the amount as well as the loading of the actuator can be reduced.

In Fig. 12 this drive system is presented with five ribs coupled to each other. The first rib element is provided with an opening where the transmission beam and the wedges are positioned. Since the beam is driven altogether by two actuators, less drives than ribs are needed. The actuators are mounted on the rear spar. When they are activated, the transmission beam to which the wedges are attached moves horizontally. This way the horizontal movement is transferred into a vertical one, pushing the slide block upward or downward. To these slide blocks the second elements or the levers are attached (see Fig. 6 and Fig. 7) leading to the wanted deflection. Due to the small gradient of the wedge most of the loading is directly transferred into the structure of the first element leading to a reduced actuator force. When the actuators are retracted the flexible region is de-cambered, an extension results in added camber. When actuated in the opposite direction a spanwise differential cambering is provided [14].

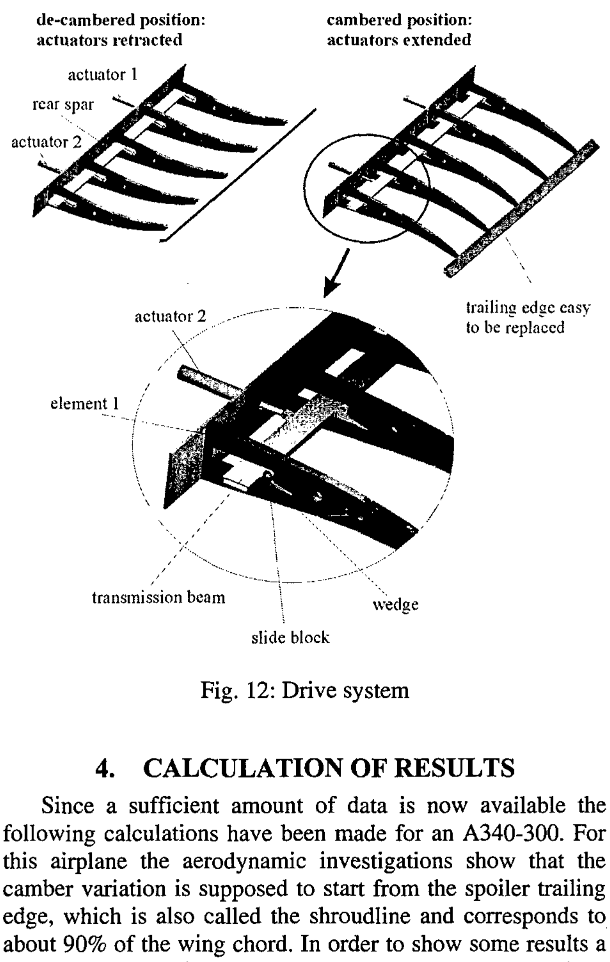

Fig. 12: Drive system

4. CALCULATION OF RESULTS

Since a sufficient amount of data is now available the following calculations have been made for an A340-300. For this airplane the aerodynamic investigations show that the camber variation is supposed to start from the spoiler trailing edge, which is also called the shroudline and corresponds to about 90% of the wing chord. In order to show some results a representative section was chosen (see Fig. 13) with defined geometry and aerodynamic loading. This section goes through the inner part of the outer Fowler flap. Here the flexible region makes up 50% of the Fowler flap chord leading to a cambering length of 840mm. The maximum camber variation shall be ±15°, which results in a deflection of ±185mm of the trailing edge. As maximum aerodynamic loading the maneuver load case is relevant. Moreover it has to be considered that this load is divided up over 21 active deformable ribs at a Fowler flap length of 10210mm

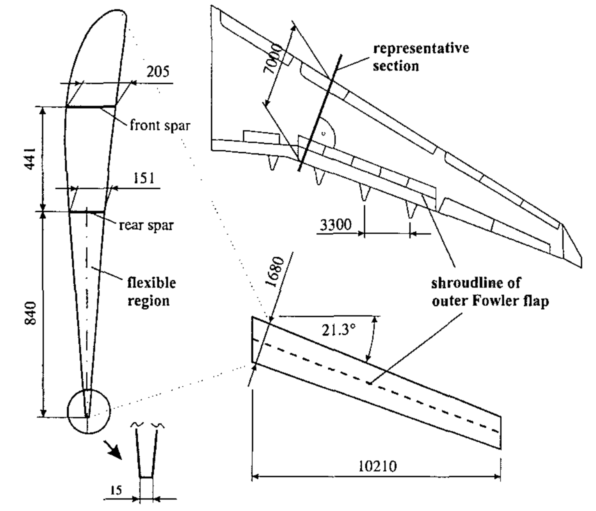

Fig. 13: Geometrical requirements

In this paper the calculation and presentation of results will concentrate on the rib structure. Therefore in Fig. 14 the following designations for the rib are chosen. The segment length indicated as l_i (i = 1, 2, ..., n) is defined describing the distance between the revolute joints (see Fig. 6 and Fig. 7, No. 8-12) whereas n indicates the number of segments. The revolute joints are now described by G_{i1} (i = 1, 2, ..., n), the prismatic joints by G_{i2} (i = 1, 2, ..., n-1). In addition the function $f_S(x)$ for the median line is introduced.

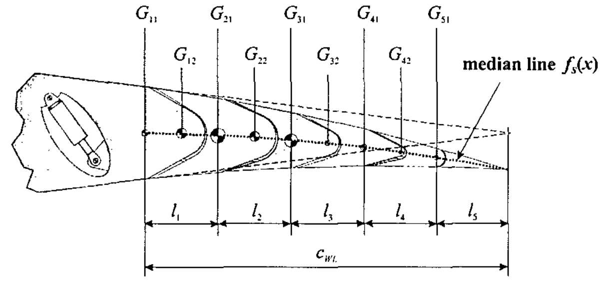

Fig. 14: Designations of rib structure

According to the defined basic requirements it is important to provide the possibility to adapt the contour towards different median lines occurring due to different aerodynamic and geometrical demands. Therefore the kinematics of the rib is investigated for three different types of functions $f_S(x)$ for the median lines which are shown in Fig. 15.

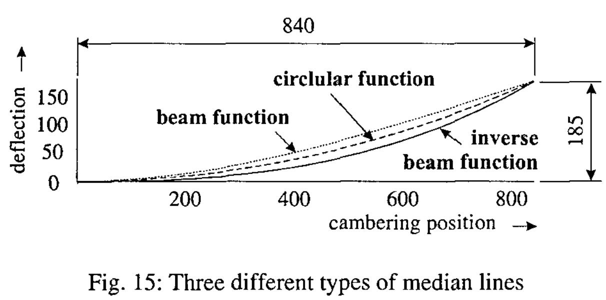

Fig. 15: Three different types of median lines

The first function is for the median line equivalent to elastic line according to Bernoulli's beam theory for a one sided rigidly clamped beam with a displacement applied to the free end.

$$f_S(x) = \frac{\Delta z}{2}\left(3\frac{x^2}{c_{WL}^2} - \frac{x^3}{c_{WL}^3}\right) \tag{1}$$

By the second function a bending line is used, too. The difference is that it is inverted meaning that the free end of equation (1) is now rigidly clamped with an angle $f_s'(x) = 0$.

$$f_S(x) = \frac{\Delta z}{3}\left(\frac{x^2}{c_{WL}^2} + 2\frac{x^3}{c_{WL}^3}\right) \tag{2}$$

For the third median line the circular function is being used. An arc of a circle is totally defined when it runs through two defined points where from one of the points the gradient is known. In this case the position of the rigidly clamped and the free displaced end is known. At the rigidly clamped end the angle is $f_s'(x) = 0$.

$$f_S(x) = \frac{1}{2}\left(\Delta z + \frac{c_{WL}^2}{\Delta z}\right) - \sqrt{\frac{1}{4}\left(\Delta z + \frac{c_{WL}^2}{\Delta z}\right)^2 - x^2} \tag{3}$$

For rib structure general formulations have been established allowing calculation of the rib geometry and the joint loading according to any given aerodynamic and geometric requirement. Parameter variations have shown that the most useful configurations occur by an amount of segments n = 4 and n = 5 which is why the following presentation of results concentrates on these two cases.

The results for the joint loading of the rib without lever (see Fig. 6) for the three median lines are shown in Fig. 16. It can be seen that independent of the number of segments and the type of median line the maximum loading appears in the front two joints G_{11} and G_{21}. Moreover, in all joints the global loading is higher at n = 5 than at n = 4. It is also obvious that the maximum loading clearly appears for the beam function, the lowest for the inverse beam function. The circular function leads to slightly higher values than the latter.

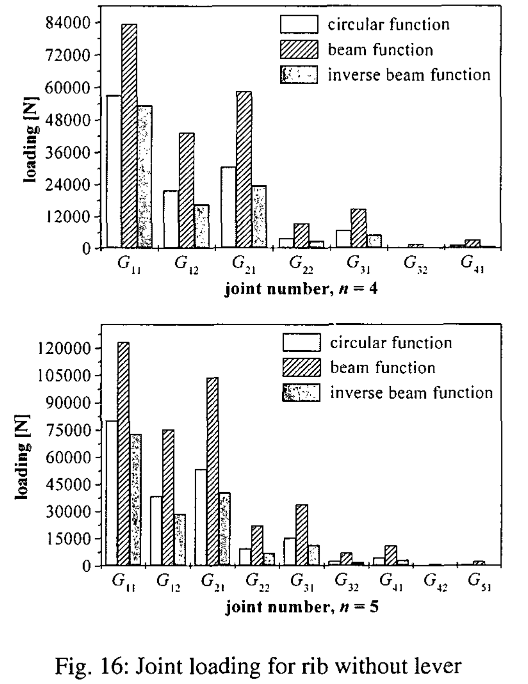

Fig. 16: Joint loading for rib without lever

The joint loading for the rib without lever is quite high, especially for the beam function. An additional lever allows a significant reduction of this loading. In this case the lever was attached to the joints G_{11} and G_{31}. As can be seen in Fig. 17 the lever relieves the front joints from the high loads. Similar to the rib without lever the beam function causes the highest loads, too. Also a higher number of segments results in higher joint loading.

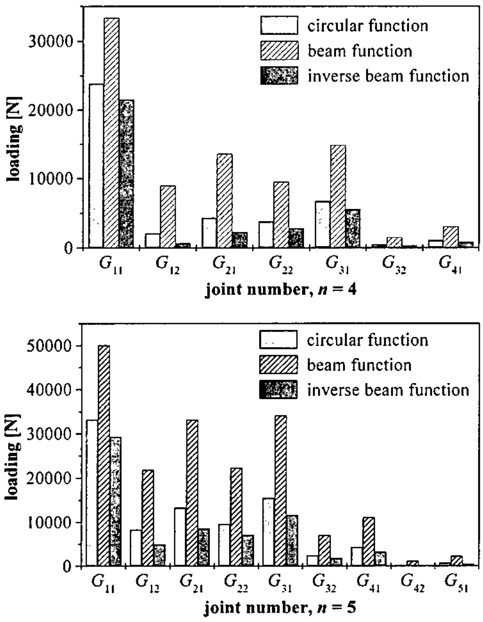

Fig. 17: Joint loading for rib with lever

A comparison of the joint loading for the rib with and without lever shows a significant reduction by the active deformable rib with lever (see Fig. 18). For joint G_{11} loading decreases by 60% and is nearly independent of the number of segments and the function for the median line. For the joints G_{12} and G_{21} improvements between 70% - 95% can be achieved. All other joint loadings stay unchanged.

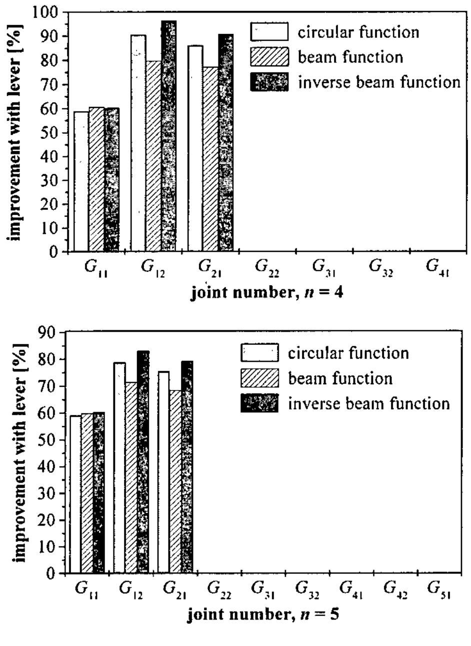

Fig. 18: Comparison of joint loading for rib with and without lever

Since the rib with an additional lever shows a significantly reduced joint loading compared to the version without (see Fig. 18) it is advantageous to use the former for the given maneuver load case. Therefore the complete rib geometry in Fig. 19 has been calculated for the preferred configuration with a lever. Since the formulations have been made in a general form it is easily possible to perform these calculations for the given median line and the calculated joint loading. In order to get a better overview the lever is not included in the illustrations of Fig. 19.

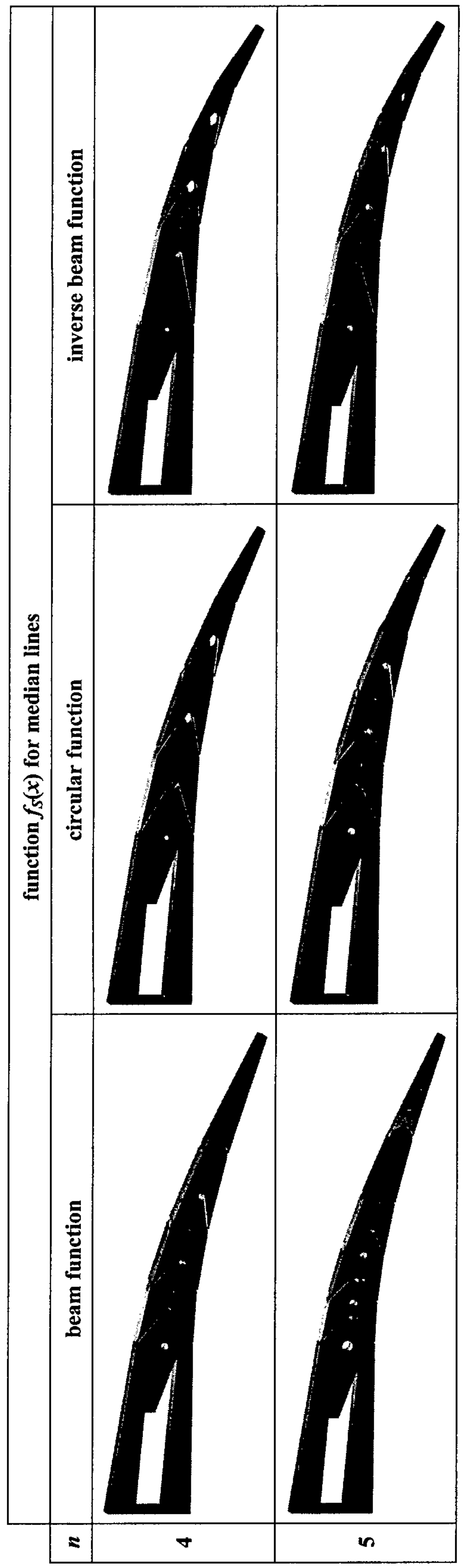

Fig. 19: Rib geometry for different types of median functions and number of segments

The first rib element is already provided with the necessary opening for the transmission beam and the wedge system of the drive system. Investigations with the finite element method (FEM) have shown that no critical deformation or strain appears. Moreover it can be seen that

depending on the median line the length of the segments varies. The stronger the curvature is the shorter the segments have to get in order to reproduce the median line in a sufficient way. Therefore, by the circular function all segments are of equal length due to the constant curvature. By the beam function the shortest segments are close to the fixed region and get longer towards the trailing edge. As to be expected by the inverse beam function, the shortest segments are at the trailing edge with increasing length towards the fixed section. The overall length of the segments gets shorter when the number of segments increases. For the rest of the elements FEM calculations have also been performed showing that here, too, no critical deformation or strain occurs.

5. CONCLUSIONS

The present paper describes an approach to achieve a chordwise as well as spanwise differential camber variation in the wings of civil transport aircraft by designing a flexible flap system for the trailing edge. According to the aerodynamic investigations the camber variation should start after 90% of the wing chord which corresponds to the shroudline. On civil transprt aircraft the ailerons and Fowler flaps are positioned in this region. Therefore the demonstrated cambering system can both be used as total replacement of an aileron and as enhancement of a Fowler flap. Because of less space being available and structural stiffness being critical it is much more demanding to enhance a given flap structure which is why the variable camber concept was presented for the enhancement of a Fowler flap. This means the trailing 50% of the Fowler flap had to be modified. As a design approach active deformable ribs were introduced into this flexible flap section. These active ribs consist of separate plate-like elements connected by revolute joints that can be driven from one single point. The rotation of the driven element is transferred gradually from element to element by these kinematics. Two variations of these kinematics were developed and different configurations were compared with each other for different types of profile contours. One system consists of the basic kinematics, the other one was enhanced by an additional lever. It was shown that the large joint loading of the solution without lever can be reduced by up to 90% using the solution with an additional lever. This makes the approach with lever advantageous for this given maneuver load case. In addition the kinematics has the advantage that by varying the distances between the revolute and prismatic joints the rib can be adjusted to nearly any desired median line. Moreover, the formulations for calculating the rib have been made in a general form and allow an easy adaptation of the rib design for different geometrical and aerodynamical requirements. Taken together the results of the investigations made this far are very promising for the continuing work on this concept.

6. ACKNOWLEDGEMENTS

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